

Radiation Effects on a Small DC-DC Converter and a Remedy by Circuit Design Technique

1 May 2002

Prepared by

C. H. TRUONG, E. J. SIMBURGER, R. C. LACOE,
J. C. ROSS, S. BROWN, and A. PRATER
Electronics and Photonics Laboratory
Laboratory Operations

K. SIRI
Electrical and Electronic Systems Department
Electronic Systems Division

Prepared for

SPACE AND MISSILE SYSTEMS CENTER
AIR FORCE SPACE COMMAND
2430 E. El Segundo Boulevard
Los Angeles Air Force Base, CA 90245

Engineering and Technology Group

APPROVED FOR PUBLIC RELEASE;
DISTRIBUTION UNLIMITED

This report was submitted by The Aerospace Corporation, El Segundo, CA 90245-4691, under Contract No. F04701-00-C-0009 with the Space and Missile Systems Center, 2430 E. El Segundo Blvd., Los Angeles Air Force Base, CA 90245. It was reviewed and approved for The Aerospace Corporation by B. Jadaszliwer, Principal Director, Electronics and Photonics Laboratory. Michael Zambrana was the project officer for the Mission-Oriented Investigation and Experimentation (MOIE) program.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

A handwritten signature in cursive script, reading "Michael Zambrana". The signature is written in dark ink and is positioned above a horizontal line.

Michael Zambrana
SMC/AXE

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 01-05-2002		2. REPORT TYPE		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Radiation Effects on a Small DC-DC Converter and a Remedy by Circuit Design Technique				5a. CONTRACT NUMBER F04701-00-C-0009	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) C. H. Truong, K. Siri, E. J. Simburger, R. C. Lacoe, J. C. Ross, S. Brown, and A. Prater				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) The Aerospace Corporation Laboratory Operations El Segundo, CA 90245-4691				8. PERFORMING ORGANIZATION REPORT NUMBER TR-2002(8555)-2	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Space and Missile Systems Center Air Force Space Command 2450 E. El Segundo Blvd. Los Angeles Air Force Base, CA 90245				10. SPONSOR/MONITOR'S ACRONYM(S) SMC	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) SMC-TR-02-27	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT This report presents the complete results of the total-dose and dose-rate testing on a typical high-efficiency, low-power, low-voltage DC-DC converter used in commercial portable devices. The purpose of these investigations was to characterize performance of the converter in radiation environment at high and low dose rates. Results of the test include time-domain performance and frequency response before and after the irradiation. The converter maintained regulation control at 100 krad/s; however, the output voltage regulation drifted-up. Adding an external standby output-voltage regulating circuit has successfully solved the problem.					
15. SUBJECT TERMS DC-DC converter, Total dose tolerance, Radiation effects, Power converter					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES 15	19a. NAME OF RESPONSIBLE PERSON Calvin Truong
a. REPORT UNCLASSIFIED	b. ABSTRACT UNCLASSIFIED	c. THIS PAGE UNCLASSIFIED			19b. TELEPHONE NUMBER (include area code) (310)336-8129

Note

The material reproduced in this report originally appeared in *GOMAC 2002 Digest of Papers*, proceedings of the Government Microcircuit Application Conference (GOMAC) and the Hardened Electronics and Radiation Technology (HEART) conference. The TR is published to document the work for the corporate record.

Contents

1.	Introduction	1
2.	Test Description	1
3.	Time Domain Performance.....	2
3.1	Output Voltage	2
3.2	Efficiency	2
3.3	Minimum Startup Voltage	3
3.4	Leakage Current.....	3
3.5	Output Voltage Ripples.....	4
3.6	Step Load Response	4
4.	Frequency Response Characteristics	4
5.	Remedy for Output-Voltage Drift-Up Problem	5
6.	Conclusions	5
	References.....	5

Figures

1.	Output voltage.	2
2.	Efficiency at light load.	2
3.	Efficiency at Full Load	3
4.	Efficiency at high input voltage.....	3
5.	Step-load response of a post-annealing unit.....	4
6.	Loop gain and phase of a new unit.	4
7.	Loop gain and phase of unit H2.....	4
8.	Loop gain and phase of unit L1.	5
9.	Stand-by output voltage regulating circuit.	5
10.	Effect of standby output voltage control.	5

Table

1. Results of Startup Voltage, Leakage Current, Ripple, Overshoots, and Undershoots	3
---	---

RADIATION EFFECTS ON A SMALL DC-DC CONVERTER AND A REMEDY BY CIRCUIT DESIGN TECHNIQUE

Calvin Truong, Kasemsan Siri, Edward Simburger, Ron Lacoe,
Jason Ross, Stephanie Brown, and Alonzo Prater

The Aerospace Corporation
Los Angeles, CA 90009
Phone: (310) 336-8129
Email: calvin.h.truong@aero.org

Abstract

This report presents the complete results of the total-dose and dose-rate testing on a typical high-efficiency, low-power, low-voltage DC-DC converter used in commercial portable devices. The purpose of these investigations was to characterize performance of the converter in radiation environment at high and low dose rates. Results of the test include time-domain performance and frequency response before and after the irradiation. The converter maintained regulation control at 100 krad/s; however, the output voltage regulation drifted-up. Adding an external standby output-voltage regulating circuit has successfully solved the problem.

1. Introduction

Low-power, low-voltage, high-efficiency, DC-DC converters are used widely in portable devices to convert unregulated battery voltage to a regulated voltage for the main load. In a space power application, these converters are also being employed in small satellite power systems due to their small size and low mass. Among various types of low-voltage and low-power DC-DC converters, the Maxim family of small converters was selected as the power-conditioning unit in several small satellite power systems at The Aerospace Corporation. The Max 710 was used in two successful Picosat flight experiments in February 2000 and September 2001. Currently, the Max 1676 was selected as

the step-up converters to convert power from a solar array to a regulated 5-V power bus for the PowerSphere project.¹

To determine the total dose tolerance of the converter in the space environment, a radiation test was performed on samples of this device. The evaluation was based on performance in time domain and frequency response before and after the irradiation. The time-domain performance includes output voltage, efficiency, startup voltage, ripple, and the overshoots and undershoots due to step load changes. The frequency response includes the control loop gain, and phase. The test was performed at three sequences: low dose-rate with power off, high dose-rate with power off, and high dose-rate with power on bias. Partial time-domain results of the first two sequences were published in a previous paper.² This report presents the complete results with the completion of the second sequence, the addition of the third sequence, post-anneal result, the frequency response data, and a solution for the voltage drift-up problem. Data from all the three sequences were included in Figures 1 to 4 and Table 1 to show the effect of dose rate and bias condition.

2. Test Description

The step-up Maxim DC-DC converters used in the testing employ conventional boost DC-DC topology with synchronous rectification that

eliminates the need for an external Schottky diode. The converter switching frequency depends on the load and input voltage, and can range up to 500 kHz. A more complete description of the converter was presented in Reference 2.

The total dose radiation test was conducted using a Cobalt-60 gamma-ray source at The Aerospace Corporation. Two bias configurations were applied in the testing. The first configuration was power-off with all input and output pins of the samples connected together. In the second bias configuration, the converter was powered by a power supply and connected to a constant-current electronic load at the output.

Three sequences of total dose test were performed. The first sequence was performed at a high dose rate of 5.73 rad (Si)/s and power-off bias condition for one sample. The second sequence was performed at a low dose rate of 0.01156 rad (Si)/s and power-off for five samples. The presented result is the average of five samples. Finally, the third sequence was performed at a high dose rate of 5.73 rad (Si)/s and power-on bias configuration.

3. Time Domain Performance

Like other commercial parts, the Max 1676 converter was not built for space applications. There were no radiation compliance issues in the design specifications for this piece part. The test results are compared to the initial performance and the specification limit here to determine the radiation-sensitive parameters and tolerance of the device.

3.1 Output Voltage

The manufacturer's specification on the output voltage is the range between 4.8 and 5.2 V. The converters regulated very well at the 5-V level during the power-off high dose rate test, as shown in Figure 1. However, the irradiation at

low dose rate resulted in an increase in the regulated voltage of the device. In this case, the output voltage increased to 6 V as the total dose reached 100 krad, well exceeding the 5.2-V regulation limit. In the case of power-on at high dose rate, a similarly increasing output voltage was observed. The output voltage drift-up was also experienced in the test of high input voltage.

3.2 Efficiency

The efficiency of the converter was measured at various load conditions and input voltages. As shown in Figure 2, at light load condition, efficiency stayed in the range of 78% to 86% for

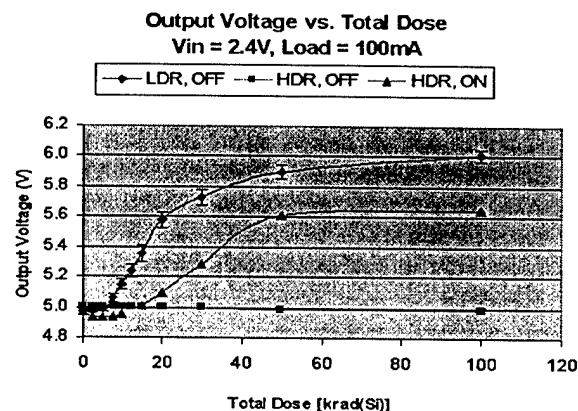


Figure 1. Output voltage.
Efficiency vs. Total Dose
Vin = 2.4V, Load = 100mA

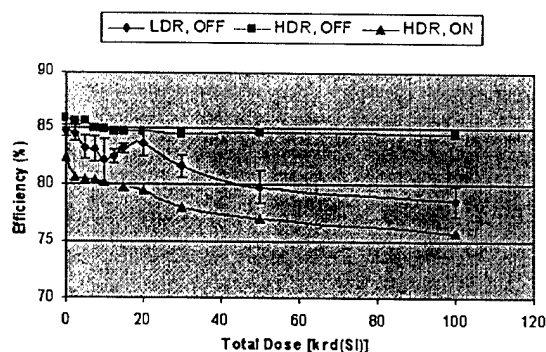


Figure 2. Efficiency at light load.

both low and high dose rates at power-off condition. Degradation caused by the irradiation effect was within 6%. A similar effect was observed in the case of power-on; the efficiency dropped only 6% from 82 to 76%. At the typical load condition of 200 mA, the effect was higher, as shown in Figure 3. Due to the increase of the input current, the efficiency reduced to 48% at low dose rate, significantly lower than the 74% at the beginning of irradiation. In the case of power-on condition, the efficiency dropped to 36%. Thus, the converter performance at higher load conditions degraded faster than at light load conditions.

At the higher input voltage of 4.5 V, the input current increased in a slower pace during the irradiation. Therefore, the converter efficiency was maintained within the range of 85 to 90%, as shown in Figure 4. The characteristic that converters can achieve higher efficiency at high input voltage condition is quite independent from total dose effects. This result has determined a favorable operating zone for the converter in system design.

3.3 Minimum Startup Voltage

The minimum voltage to start up the converters was measured at light load (100 ma) condition. Table 1 shows results of three test sequences and the corresponding post-annealing measurement.

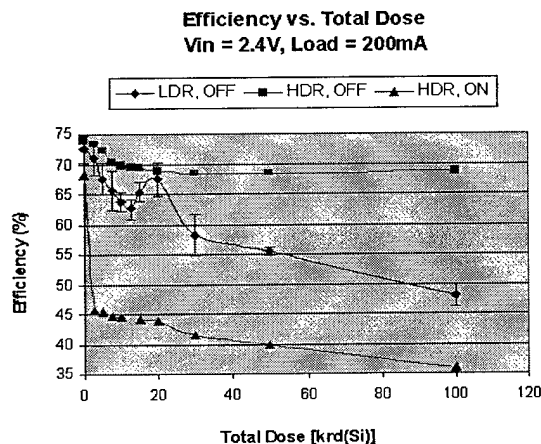


Figure 3. Efficiency at full load.

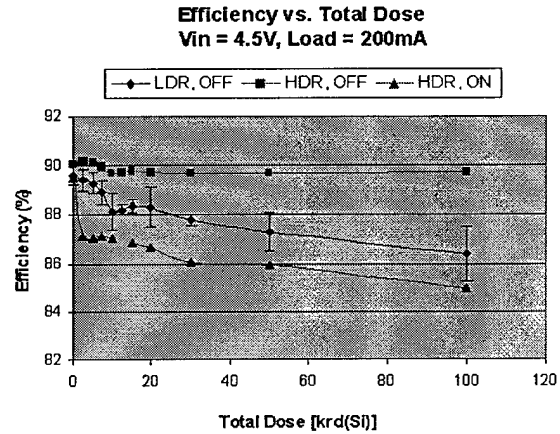


Figure 4. Efficiency at high input voltage.

Table 1. Results of Startup Voltage, Leakage Current, Ripple, Overshoots, and Undershoots

Measurement	High Dose Rate, Power Off	Low Dose Rate, Power Off	High Dose Rate, Power On
Min Startup Voltage [V]	1.48 – 1.55	1.51 – 1.60	1.58 – 1.76
Post-annealing	1.51	1.59	1.76
Leakage Current [mA]	0.21 – 0.36	0.18 – 0.34	0.21 – 0.41
Post-annealing	0.36	0.30	0.26
Ripple [mV]	125 – 200	100 – 124	90 – 130
Post-annealing	130	120	100
Overshoot [mV]	N/A	9 – 16	10 – 40
Post-annealing		14	10
Undershoot	N/A	17 – 26	15 – 24
Post-annealing		23	18

At two dose rates of power-off condition, the Max 1676 converters required only less than 1.6 V for startup through 100 krad. A slightly higher startup voltage of 1.76 V was required in the case of power-on condition, but this number is not very far from the others. The startup voltage is not as low as specified in the data sheet; however, the increase due to the radiation effect was within 10%.

3.4 Leakage Current

The leakage current was measured at 2.4 V input and no load condition. As shown in Table 1, the leakage current for all cases was in the range of 20 to 40 ma, with the low dose rate data increased at a slower pace. The result appears

higher than the manufacturer's specification for commercial applications. Sufficient power budget should be reserved for the device at no-load condition.

3.5 Output Voltage Ripples

The output voltage ripples in all test conditions were within 200 mV through 100 krad. As shown in Table 1, the ripples in post-annealing units recovered back to as low as 130 mV.

3.6 Step Load Response

The output voltage overshoot and undershoot magnitudes during step-load transition from light to mid load were measured at low input voltage. The overshoot was within 50 mV, and the undershoot was within 30 mV during the 100-krad total-dose irradiation. These magnitudes are within 1% of the output voltage. The regulation control was within the specification for commercial applications. Figure 5 shows the step load response of a unit after low dose-rate test and annealing. As functioning before irradiation, the unit adjusted its switching frequency smoothly in response to the load change.

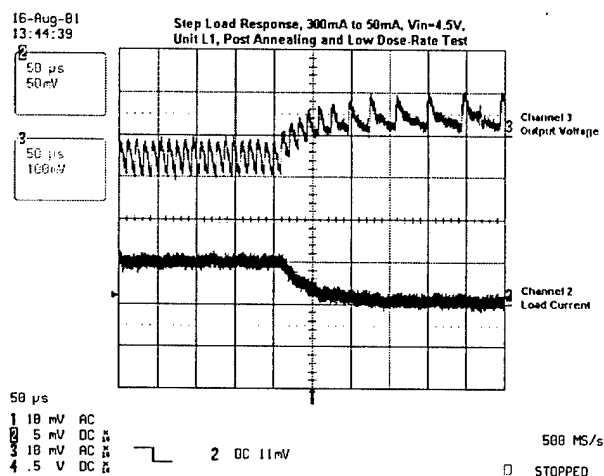


Figure 5. Step-load response of a post-annealing unit.

4. Frequency Response Characteristics

The control loop gain and phase were measured on two post-annealing units: unit H2 used for high dose rate test, and another unit, L1, used for low dose rate test. Comparing the frequency response of a new converter in Figure 6 and the two irradiated converters in Figures 7 and 8, the loop gain and phase results appeared quite consistent. The phase margin stayed in the range of 70 ± 2 degrees, and the gain margin maintained at 9 dB. The unity bandwidth kept unchanged around 19 kHz. This result verifies the robust regulation control performance in the time domain measurement.

5. Remedy for Output-Voltage Drift-Up Problem

At 100 krad total dose, the converters still operated under regulation control and little noise.

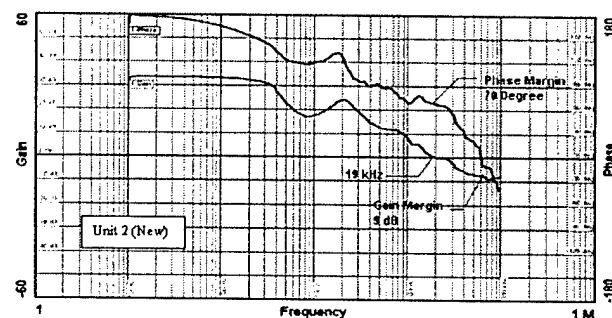


Figure 6. Loop gain and phase of a new unit.

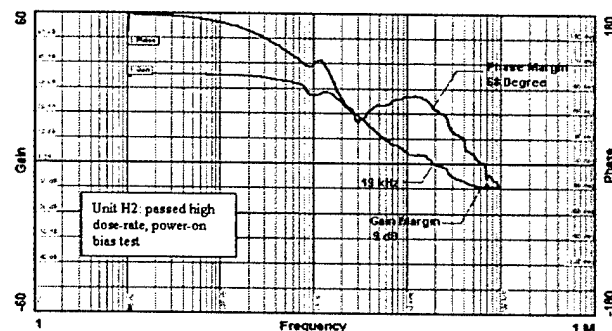


Figure 7. Loop gain and phase of unit H2.

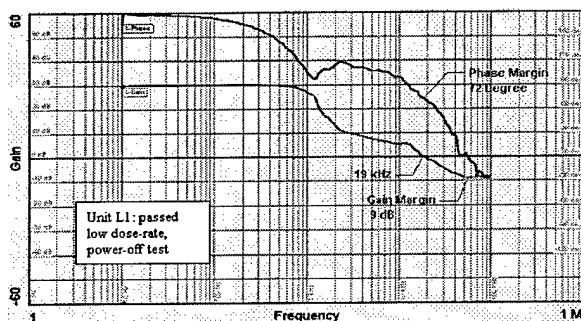


Figure 8. Loop gain and phase of unit L1.

The only problem is the output voltage drift-up to 6 V, exceeding the 5.2-V regulation range. Since this device was built for commercial application and a schematic was not available, a possible solution to keep the output voltage in the regulation zone without modifying the commercial design was to add an external control circuit from outside of the chip via available pins. A non-inverting level detector circuit with hysteresis was used to activate the shutdown function of the converter via the shutdown pin, as shown in Figure 9. During normal operation, the circuit is in standby mode. It enters the shutdown mode when the output voltage exceeds the upper bound of 5.3 V and returns to normal operation when it hits the lower bound of 5.1 V. As shown in Figure 10, after the circuit was connected to the shutdown pin of the converter L2, a post-annealing unit experienced low dose rate test, this shutdown-and-release operation effectively pulled down the output voltage from 5.5 V to an average level of 5.2 V with tolerable ripples.

6. Conclusions

Total dose test results for a typical low-voltage and low-power DC-DC converter have been discussed. The commercial device was able to function and maintain regulation control throughout the total dose irradiation at high and low dose rates. Efficiency remains over 80% at high input voltage and light load conditions. The only significant problem, output voltage drift-up, was fixed by implementing a standby output

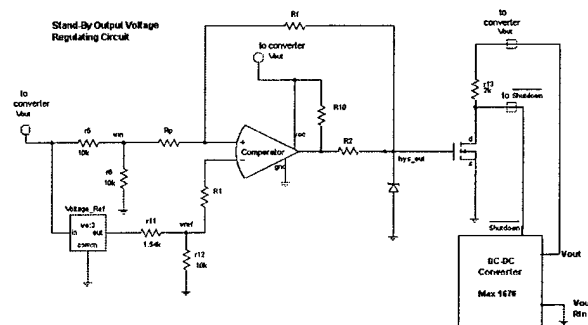


Figure 9. Stand-by output voltage regulating circuit.

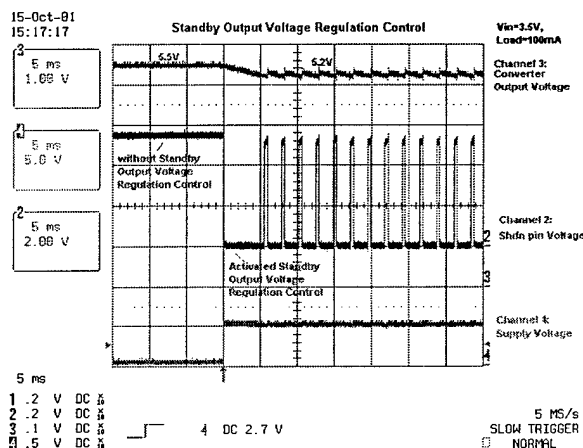


Figure 10. Effect of standby output voltage control.

voltage-regulating circuit. Finally, the results of this experiment demonstrated that the testing of a highly integrated electronic device as a total system in a radiation environment could be a useful tool in determining the system-level effects of radiation on system performance.

References

1. A. Prater, et al., "PowerSphere Power System Demonstration Station," 28th IEEE Photovoltaic Specialists Conference, September 2000.
2. C. H. Truong, et al., "Radiation Test on a Small DC-DC Converter," 2001 Digest of Papers, Government Microcircuit Applications.